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ON
SIMULATED WAVE-RIDING DOLPHINS
by
Byrne Perry, A.J. Acosta and T.Kiceniuk

HYDRODYNAMICS LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
1201 E. CALIFORNIA STREET
PASADENA 4, CALIFORNIA

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ON SIMULATED WAVE-RIDING DOLPHINS

by

Byrne Perry⁽¹⁾, A. J. Acosta⁽²⁾ and Taras Kiceniuk⁽²⁾

(1) Department of Civil Engineering, Stanford University
Stanford, California

(2) Hydrodynamics Laboratory, California Institute of
Technology, Pasadena, California

August 1961

ACKNOWLEDGMENT

This work was supported, in part, by
the Department of the Navy, under
Contract N 123 (60530) 24917A.

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Background

The explanation of the mechanism by which dolphins are able to ride bow waves of ships, or natural surf and wind-generated waves, has stimulated much discussion and controversy. Since an excellent summary of previous research on the wave-riding problem has been given by Fejer and Backus (1),* only a few remarks by way of review will be given here.

Although dolphins had been observed riding on bow waves of ships many times over the years, Woodcock (2, 3) published the first account which included considerations of the forces estimated to be required. Shortly thereafter, Woodcock and McBride (4) undertook to explain in more detail the nature of these forces. They found that a two hundred pound dolphin submerged in sea water would have, at most, a net weight of 9.2 lbs. The component of this weight in the direction of the local flow was thus shown to be too small to overcome the expected viscous drag -- unless the dolphin was in some manner able to maintain a laminar flow over his body surface. The Reynolds number for these observations was 8.4×10^6 based on body length. For rigid bodies tested under many conditions it is known that at such a Reynolds number the boundary layer is almost certainly turbulent; hence, the conclusion would follow that the dolphin had achieved the surprising feat of maintaining a laminar boundary layer (and hence, very low drag) at a very high Reynolds number.

It was Hayes (5) who pointed out that it was the component of the total weight rather than the net weight in the direction of the local flow that provided the thrust. With this force available, there is no need to suppose the dolphin has a viscous drag appreciably lower than any other streamlined body moving at the same Reynolds number.

In spite of the lucid arguments set forth by Hayes, some workers remain unconvinced. Scholander's experiments in the open sea (6),

*Numbers in parentheses designate references at end of text.

convinced him that the Hayes explanation was not satisfactory. Scholander and Hayes (7,8) thereupon arrived at an impasse, with Scholander suggesting that further experiments be conducted under better-controlled conditions.

In discussing these considerations with Prof. Scholander, it occurred to the present writers that the Free-Surface Water Tunnel in the Hydrodynamics Laboratory at this Institute, could be used to help resolve this controversy.

Apparatus and Experimental Procedure

At tunnel operating speeds approximating 7 feet per second, it is possible to establish a stable, standing wave in the working section of the Free-Surface Water Tunnel (9). Such a wave was formed and the simulated dolphin model (consisting of a streamlined body of revolution two inches in diameter and approximately one foot long) was immersed in the wave and the hydrodynamic reactions were measured. The test body, strut support, and force balance assembly are shown in Fig. 1. Extensive force measurements had already been made on this body in previous investigations (10) using wind tunnel, water tunnel and drop tank facilities, and were therefore available for comparison. The configuration of this body, however, had been slightly modified for the present experiments by replacing the original tail and boom assembly with a shorter one. Also, an adjustable streamlined strut had been attached to this boom, thereby permitting the attitude of the test body to be determined within an angle of one-half degree.

Prior to starting the tunnel, tare forces were measured with the test body in air, at each of the angles of the test body employed in the experiment. By means of an elevating mechanism, the balance and body assembly were lowered until the centerline of the body was at a depth of about 0.2 ft. The buoyant force acting on the body in still water was then measured. The tunnel was started and the standing wave established. Force readings at the two tunnel locations were made for angles of 0° and $\pm 8^\circ$ at various submergences.

Position 1 (fig. 2), was located on the upstream slope of the wave, considerably ahead of the crest. It had been hoped that the body could be located somewhat farther downstream, but this could not be done easily because of interference with a tunnel structural member. Position 2 (Fig. 3), was in the trough of the wave. The water velocity in these tests was of necessity near the critical channel velocity, but varied locally with position along the wave. A miniature HRS current meter about one-half inch in diameter was used to measure these velocities at the same longitudinal position and depth in the tunnel as the midpoint of the test body. These data are summarized in Table I as well as are some other conditions not described.

Observations and Analysis of Data

When the test body was aligned with the slope of the water surface and submerged beneath the upstream slope of the wave in position 1, it was immediately apparent that a small, forward thrust between 0.007 and 0.11 lbs was measured (see runs 14-17). However, when the body was located in the trough of the wave at a similar submergence (runs 8, 9, 10) the body experienced a drag force ranging from 0.07 lb to 0.106 lb. These figures can be compared to the still-water buoyant force of 0.78 lb to establish scale. Although no attempt was made to find the optimum location of the body with respect to the wave insofar as thrust is concerned, it is clear that a net thrust can be achieved with a rigid streamline body under even the gentle slope of the wave produced in the tunnel.

The observed thrust varies with depth and changes to a drag both when the body broaches and when the submergence exceeds about three diameters of the body. It should be remembered that the drag of the strut is included in these results so that the present data do not reflect the body drag alone. The submergence for least drag observed herein -- about one body diameter -- is roughly the same as that reported for dolphins in bow waves.

Further insight into the mechanics of the force system acting on the body is obtained by resolving the forces along axes parallel to and perpendicular to the local flow angle (5). For example, for run 14 of

Table I (corresponding to Fig. 2), the resistance parallel to the local flow is 0.054 lb and the force normal to the flow (or free surface) is 0.745 lb, with the estimated local flow angle of 5° . This latter force, perpendicular to the wave surface, can be regarded as an inclined buoyant force as mentioned by Hayes. These forces, it must be recalled, are hydrodynamic in origin and do not include the body weight. Let it be supposed now that the self-propelling capability of a body, whose weight is equal to that of the displaced fluid, is to be determined. This weight of 0.777 lb resolved along the direction of flow must exceed the flow resistance of 0.054 lb. For the present example, this force is not only exceeded but there is, in fact, a net propelling force of 0.013 lb available. The forces are not precisely in equilibrium for this example; the body, if free, would tend to sink to a slightly greater depth, where the vertical force is seen to be larger.

The flow resistance of 0.055 lb resolved along the local flow angle is roughly comparable to the drag measured in the trough of the wave (run 8) and both are typical of viscous drag measurements in a turbulent flow (9, 11). Laminar skin friction is therefore seen not to be a necessary condition for bow wave riding as was originally contained in the suggestion by Woodcock.

It is also interesting to observe that the vertical forces both in the slope of the wave and in the trough differ noticeably from the buoyant force in still water. This is thought to be due to a combination of two effects: the well-known repulsion experienced by a submerged body moving under an otherwise flat, free surface, and more important, the curvature of the local streamlines. Summary calculations have shown the contributions of the latter term to the lift force to be of the correct magnitude.

Conclusion

The mere existence of the measured forward-acting thrust on the test body in a wave demonstrates that a rigid body with turbulent flow can perform the wave riding trick. Analysis of the measurements shows further that the force system is equivalent to a dynamic buoyant

force perpendicular to the inclined wave surface and a resistance parallel to this surface. The dynamic buoyancy is approximately equal to the weight of the displaced liquid, while the viscous resistance is substantially equal to that measured on the body when not in the wave.

In spite of these incomplete experimental results, it appears inescapable that Hayes' arguments are substantially correct.

TABLE I

Run No.	Tunnel Position	Angle	Depth	Drag*	Lift	Water Velocity	Remarks
1	1 <i>PHOTO</i>	-10 deg.	0.25 ft.	0.000 lb.	0.774 lb.	0.00 ft./sec.	
2	1	0	0.1	0.000	0.776	0.00	
3	1	0	0.2	0.000	0.777	0.00	Stationary
4	1	- 8	0.25	0.000	0.776	0.00	
5	1	+ 8	0.15	0.000	0.778	0.00	
6	1	0	0.2	0.031	0.889	2.78	Flat free surface (no standing wave)
7	1	0	0.2	0.032	0.775	3.54	
8	2 <i>PHOTO</i>	0	0.2	0.071	0.842	7.24	
9	2	+ 8	0.25	0.106	0.900	7.22	In trough of wave
10	2	- 8	0.05	0.070	0.829	7.26	
11	1	+ 8	0.2	0.059	1.022	7.08	
12	1	0	0.2	0.001	0.870	7.12	
13	1	- 8	0.1	0.008	0.641	7.02	
14	1 <i>#17</i>	- 8	0.15	-0.011	0.748	7.08	Forward slope of wave
15	1 <i>#2</i>	- 8	0.2	-0.007	0.793	7.02	
16	1	- 8	0.25	-0.009	0.800	7.04	
17	1	- 8	0.35	-0.001	0.821	7.02	
18	1	- 8	0.45	0.006	0.824	7.00	

* Negative values imply thrust.

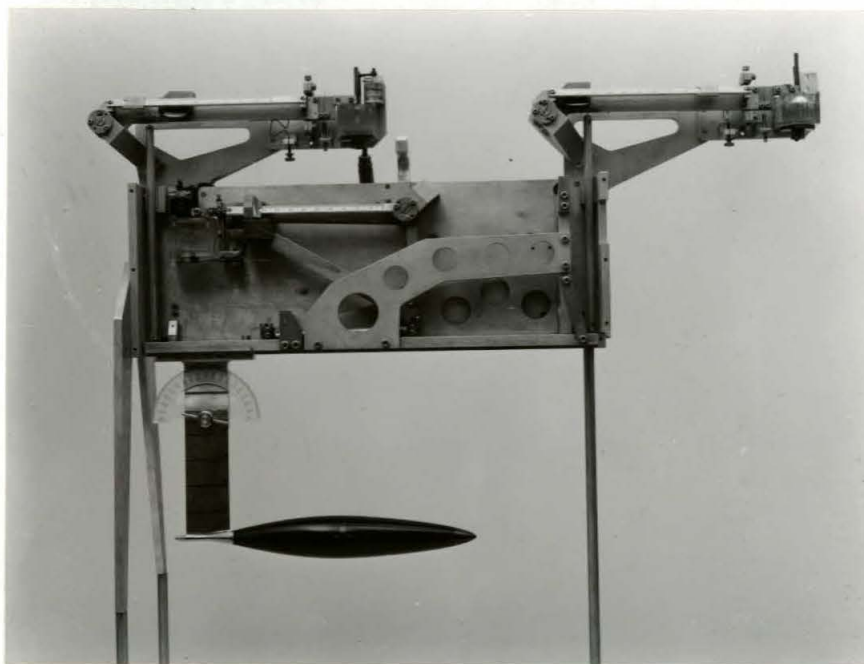


Figure 1. The "dolphin-like body" mounted on the 3-component force balance used in these experiments

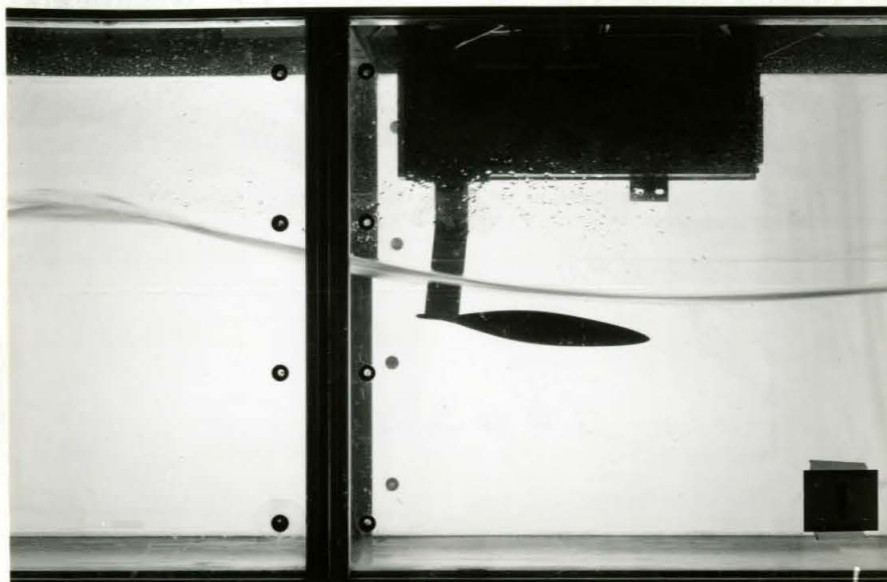


Figure 2. "Dolphin-Body" located at tunnel position No. 1 on the forward slope of a standing wave. Net forward thrust = 0.007 lb at a velocity of 7.02 fps.

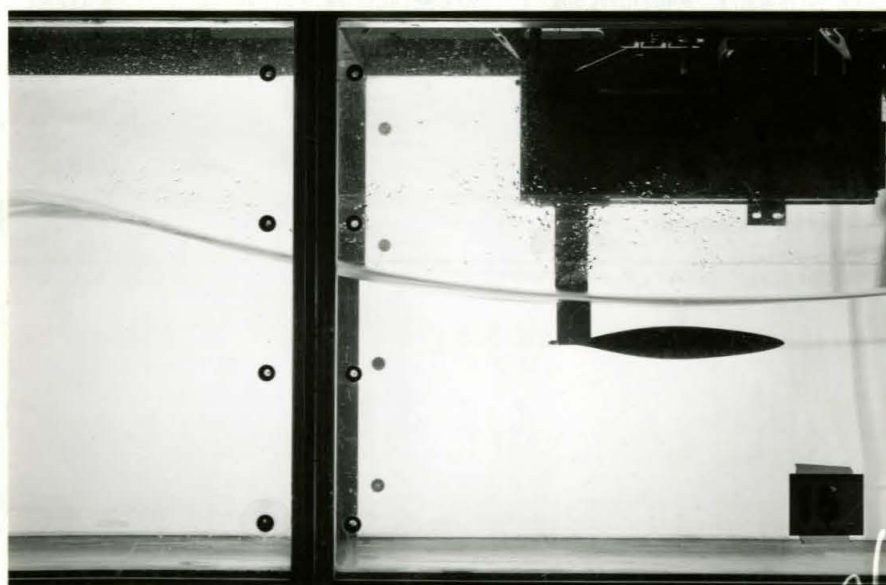


Figure 3. "Dolphin-Body" located at tunnel position No. 2 in the trough of the standing wave. Net drag = .071 lb at 7.24 fps. Note the dye streak ahead of the model near the model center line.